Discontinuous Rating Curves

for Pigeon Roost and Cuffawa Creeks in Northern Mississippi

April 1960

ARS 41-36
Agricultural Research Service
UNITED STATES DEPARTMENT OF AGRICULTURE

CONTENTS

Prepared by
Soil and Water Conservation Research Division
Agricultural Research Service

in cooperation with

Mississippi State University
and
University of Mississippi

DISCONTINUOUS RATING CURVES FOR PIGEON ROOST AND CUFFAWA CREEKS IN NORTHERN MISSISSIPPI

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INTRODUCTION

Streamflow measurements in northern Mississippi at several gaging stations on Pigeon Roost Creek and its major tributary Cuffawa Creek have been found to define discontinuous stage-discharge relationships. Within a limited range of gage height for the particular station, the flow at any stage may be double at one time what it is at another. But above and below this range, the streamflow measurements define reasonably stable stage-discharge relationships. The observed discontinuities, which had not been expected when the gaging stations were installed, required (a) an analysis of the mechanics of the streams to learn what was actually happening and (b) some revision of standard procedures for computing streamflow as well as special care in computing sediment discharges.

This report has three purposes. The first is to show that discontinuities in the stage-discharge relationship occur in some creeks that flow over beds of sand and thereby confirm in the field the finding by Brooks (3)[2] from flume studies that more than one mean velocity may exist for a given slope, bed material, and hydraulic radius. The second purpose is to explain the discontinuities. The third is to give suggestions on the practical computation of streamflow from discharge measurements and sediment discharge from samples of the water-sediment mixture when the stage-discharge relationship is discontinuous.

General background information on the drainage area and gaging stations is followed by a description of the discontinuous stage-discharge relationships at the several stations. Next, the reasons for the discontinuities are explained through a consideration of the mechanics of the streams. Finally, the practical computation of streamflow and sediment records is discussed for stations that have discontinuous stage-discharge relationships.

The information of this report, covering a period from October 1, 1956, to March 31, 1959, reflects the results of one phase of a large and continuing sedimentation research program of the Agricultural Research Service, USDA, involving 12 gaging stations. Streamflow measurements and gage-height records through April 30, 1958, were collected under financial arrangement with the U. S. Geological Survey, J. E. Bowie, engineer in charge, for the Agricultural Research Service. After April 30, 1958, they were obtained under the supervision of H. B. Osborn, ARS. The sediment samples were collected and analyzed under the direction of R. F. Piest, hydraulic engineer, ARS, first with the Geological Survey.

DEFINITIONS

Some of the terms in this report can be better understood through the following definitions and explanations.

A <u>discontinuous stage-discharge relationship</u> is a relationship between stage and rate of steady flow that has at least two parts that are not connected by a smooth transition. That is, the discharge is not a continuous and single-valued function of the stage.

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[2] Numbers in parentheses refer to Literature Cited, p. 31.

A discontinuous rating curve is the graphical expression of a discontinuous stage-discharge relationship.

The configuration of a streambed may be described as a dune bed, a plane bed, or an antidune bed. The dune bed is characterized by irregular sand dunes that usually feel loose and unstable. Measured depths over a dune bed are variable. A plane bed, though generally rougher than a plane bed in a flume, has a smooth, firm feeling. Measured depths of flow change slowly and regularly with lateral or longitudinal distance in the stream. An object placed on such a bed seems to settle into it because of scour rather than because of looseness of arrangement of the sand grains. An antidune bed has sand waves of fairly regular height and wave length. The bed feels firm to the touch but scours very rapidly around an object that is placed on it. Standing waves on the water surface are about in phase with the sand waves.

A rise as the term is used by hydrographers is a runoff event too small to be described as a flood. In full meaning it includes the peak and recession stages of the runoff event as well as its rising stage.

Shifting is said to occur if a stage-discharge relationship or a sediment rating curve is displaced, usually temporarily, to make it more consistent with a streamflow measurement or a sediment discharge measurement or other pertinent information. Usually, a stage-discharge relationship is shifted by applying an adjustment to the observed gage heights.

The shear velocity is defined as $\sqrt{gRS}$ in which g is the gravity constant, R is the hydraulic radius, and S is the slope of the energy gradient. It is the measure of the shear that has the dimensions of a velocity.

Total sediment discharge is the total quantity of sediment, as measured by dry weight or volume, that is discharged by a stream during a given time.

Measured sediment discharge is the suspended-sediment discharge that can be computed from water discharge and the concentration of depth-integrated (or equivalent) sediment samples.

Unmeasured sediment discharge is the difference between total sediment discharge and measured sediment discharge. It consists of the bed-load discharge, which is the discharge of particles that slide, roll, or skip along the bed and very close to it, and part of the suspended-sediment discharge in the zone too close to the streambed to be sampled by the depth-integrating sediment samplers. Part of the suspended-sediment discharge in this unsampled zone is included in the measured sediment discharge.

Bed-material discharge and bed-material concentration mean, respectively, the discharge and the concentration of sediment particles of the size found in appreciable quantities in the streambed. The total sediment discharge is made up of wash load and bed-material discharge. A less precise but more readily understandable substitute for the term "bed-material discharge" is "discharge of sands," because little silt or clay is found in the streambeds of Pigeon Roost Creek and its principal tributaries.

PIGEON ROOST CREEK DRAINAGE AREA

Pigeon Roost Creek, a part of the Coldwater River system in northern Mississippi, drains an area southwest of Holly Springs. Some bottom lands and some lands along the crests of rounded ridges are cultivated, but comparatively few slopes in the drainage area are tilled. Hillsides are generally steep and in woods or pasture. The area is dissected by streams and by many gullies, some of which are actively eroding. Most gullies extend downward into the marine sands that underlie the area. These sands are relatively uniform in particle size throughout the drainage area. Hence, the sands in the beds of the streams are unusually uniform in size. The median particle size of sediment

from most streambed samples is about 0.4 millimeter, and only a few percent of the particles are either smaller than 0.125 millimeter or larger than 0.7 millimeter.

Streams in the drainage area of Pigeon Roost Creek look much alike. The banks are generally well stabilized and scour little. The larger streams flow in excavated channels that are about uniform in width and straight or gently curving. Because the transported sands are nearly uniform in size and the channels are usually straight, the streambeds are generally about level from bank to bank and have fairly uniform bottom slopes along a given reach of channel. Except in a few very small streams, riffles and pools are almost entirely absent. The larger streams have slopes of about 6 to 10 feet per mile; the smaller streams are much steeper.

Annual precipitation on the drainage area is about 55 inches; runoff from nearby areas that have many years of streamflow records is about 20 inches per year. Direct runoff is flashy. Much of it normally occurs during the winter.

GAGING STATIONS

Discontinuous stage-discharge relationships have been defined for gaging stations 12, 17, 32, 34, and 35. Each of these stations consists of a water-stage recorder in a wooden shelter (fig. 1) that is mounted on a corrugated-pipe well and attached to a bridge.

Figure 1.--Goging stotion 34 on Pigeon Roost Creek ot o low flow of obout 45 cubic feet per second. The sond bed is entirely covered with obout 0.4 foot of woter. U.S. D-49 sediment sompler with ouxiliory 50-pound weight is suspended from the box on the bridge.

Streamflow measurements are made by wading or from the bridge, except that a cableway was built in August 1958 for high-flow measurements at station 34. The channels near the gages are excavated through flat bottom land and are straight. However, two channels join 300 feet upstream from station 12. Hence, the flow at this station is not completely straightened out at the gage, and the slope of the stream sometimes is much different if measured on one bank than if measured on the other. The confluence of Dry Fork and Cuffawa Creeks is 1,100 feet upstream from station 32. The flow at station 32 is straightened out but probably not thoroughly mixed. Pertinent information on each station is listed in table 1.

The stream widths in table 1 are typical for the range of stage at which the stage-discharge relationship is discontinuous. The slopes are based on one to three determinations of water-surface slope by levels at each station and should be within about 15 percent of an average slope for a steady flow except at station 12 where the slope is variable and uncertain.

TABLE 1.--Gaging stations for which discontinuous stage-discharge relationships have been defined

Station No.	Stream	Drainage area	Approximate slope	Approximate width
		Sq. miles		*Feet*
12..........	Pigeon Roost Creek..	35.6	0.002±	85
17..........	Pigeon Roost Creek..	50.2	.0015	60
32..........	Cuffawa Creek.......	31.3	.0020	75
34..........	Pigeon Roost Creek..	117	.0011	75
35..........	Cuffawa Creek.......	11.8	.0018	60

The streambeds at each of the five gaging stations are composed of the uniform sand typical of the drainage basin. The sand at low streamflow is in soft dunes; at certain intermediate stages, in a rather firm and uniform bed; and at high flows, in antidunes along the middle of the channel, presumably bordered by a firm and uniform bed. The antidunes cannot be seen, but their presence is indicated by large standing waves, which usually form at high flows. (See figs. 2 and 3.) Neither gravel nor boulders are in the streambed.

Seven gaging stations on tributaries of Pigeon Roost Creek and Cuffawa Creek have stage-discharge relationships that show no discontinuities. Their drainage areas are as small as 0.177 square mile and as large as 8.64 square miles. Bed slopes range from about 0.0035 to 0.010. In general, the lateral distribution of flow is less uniform than for the gaging stations on the larger channels. At six of the seven stations (one of the seven does not have a sand bed) the beds are frequently plane or have antidunes along the middle of the channels during periods of flow.

DISCONTINUOUS STAGE-DISCHARGE RELATIONSHIPS

The equivalent of a discontinuous stage-discharge relationship has been reported by Brooks (3). His laboratory results showed that two widely different rates of flow could occur for certain combinations of bed material, slope, and depth because of large changes in resistance to flow. Vanoni and Brooks (6) have shown that this large difference in resistance to flow is due mainly to changes in bed configuration. The discontinuous rating curves for five gaging stations on Pigeon Roost or Cuffawa Creek support these laboratory findings.

Figure 2.--Standing-wave flow 500 feet downstream from station 12 on Pigeon Roost Creek on May 1, 1958, o- a discharge of about 1,750 cubic feet per second.

Figure 3.--Highly turbulent standing-wave flow at station 32 on Cuffawa Creek on May 1, 1958, at a discharge of about 2,000 cubic feet per second.

Station 34

The discontinuity in the stage-discharge relationship was perhaps more apparent at station 34 than at the other gaging stations for which it has been defined. Also, the first intensive fieldwork to define such a relationship was done at station 34. Hence, the relationship for this station is discussed in considerable detail.

The streamflow measurements made at station 34 between October 1, 1956, and September 30, 1957, defined two distinct curves of stage-discharge relationship that overlap at gage heights roughly 4 to 5 feet. (See fig. 4.) At times the low curve of the relationship applies as high as 6.2 feet, and the high curve sometimes applies as low as about 3.5 feet. These extreme limits of application would not apply to any one rise, but were indicated by gage-height records over a period of more than 2 years.

Measurements with mean velocities higher than 4.8 feet per second define the high curve of the stage-discharge relationship, and those with mean velocities lower than 3.0 feet per second define the low curve of the stage-discharge relationship. Of the first 100 measurements that were made, only 1 or 2 had mean velocities between 3.0 and 4.8 feet per second, although many higher and lower mean velocities were reported. Personal observation by the writer and oral comments by other hydrographers indicate that the mean velocities 3.0 feet per second or less were for flow over dunes. When the mean velocity was 4.8 feet per second or more, the flow was not waded and direct observations of bed configuration were not made. As will be seen later, mean velocities between 3.0 and 4.8 feet per second may occur during the transition between the two curves of figure 4 while the flow is changing.

Hydrographers who made the streamflow measurements first thought that the discontinuity in the stage-discharge relationship might be due to incorrect gage-height record on the water-stage recorder. Therefore, two staff gages were installed to determine whether the recorded gage heights were representative of water-surface elevations that were unaffected by high velocities near the middle of the channel. One staff gage was close to the right bank where the velocity is low, and the other was attached to the gage well. Comparative readings on the two staff gages usually agreed within a few hundredths or a tenth of a foot and showed no sudden disagreement at stages where the stage-discharge relationship became discontinuous. The water-stage recorder was set to give the same numerical readings as the staff gage that was attached to the recorder well.

Streamflow measurements made on the rise of April 3-4 and that of April 14-16, 1958, give a good idea of the behavior of the flow and the gage-height trace during recessions of flow at the gaging station. Measurement 1 on April 3 while the stage was rising plotted close to the low-velocity curve. (See fig. 5 on which the curves of fig. 4 are redrawn.) Measurement 2, also on a rising stage, was close to the high-velocity curve. Measurement 3 was made when flow outside the main channel was about 60 cubic feet per second, but the measurement is somewhat questionable and was assumed to show too little flow because the current meter repeatedly fouled with trash. Measurements 4 and 5 taken during a falling stage plotted on the high-velocity curve. Measurements 6 through 8 were made in the transition between the two curves as the flow further decreased. Measurements 9 and 10 were back on the low-velocity curve. The streamflow measurements on April 15-16 were made after the transition from the high-velocity curve to the low-velocity curve had begun. Measurements 11 through 13 were made during the transition, and measurements 14 through 17 were made when the stage-discharge relationship was close to the low-velocity curve. The approximate times, gage heights, and rates of flow of these measurements are shown in figures 6 and 7.

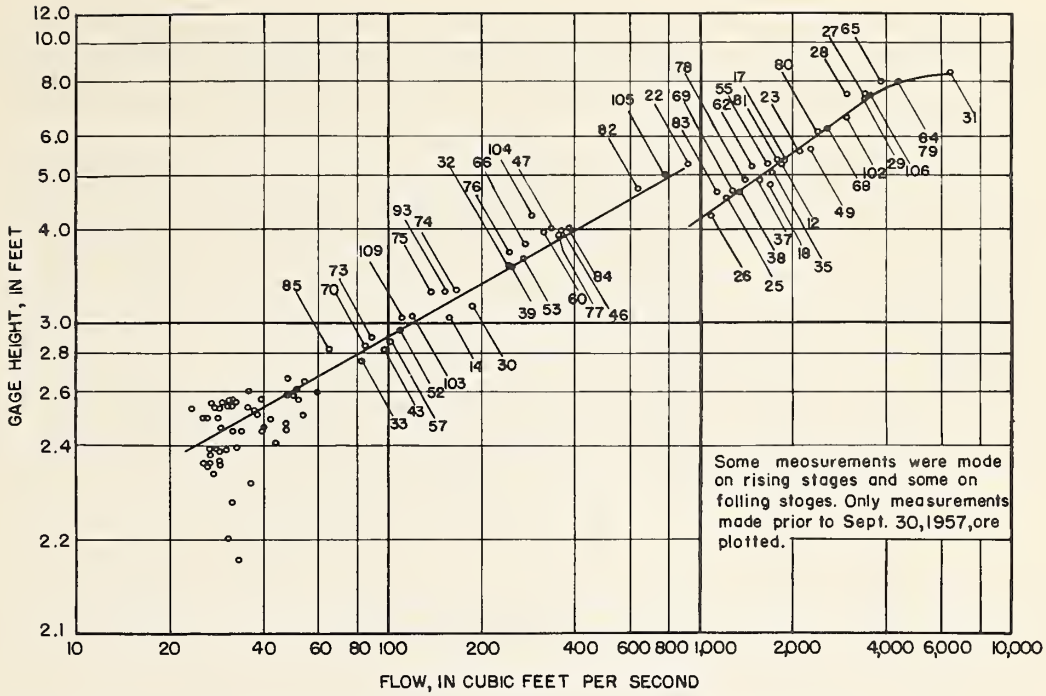


Figure 4.--Stage-discharge relationship for station 34 on Pigeon Roost Creek, Miss.

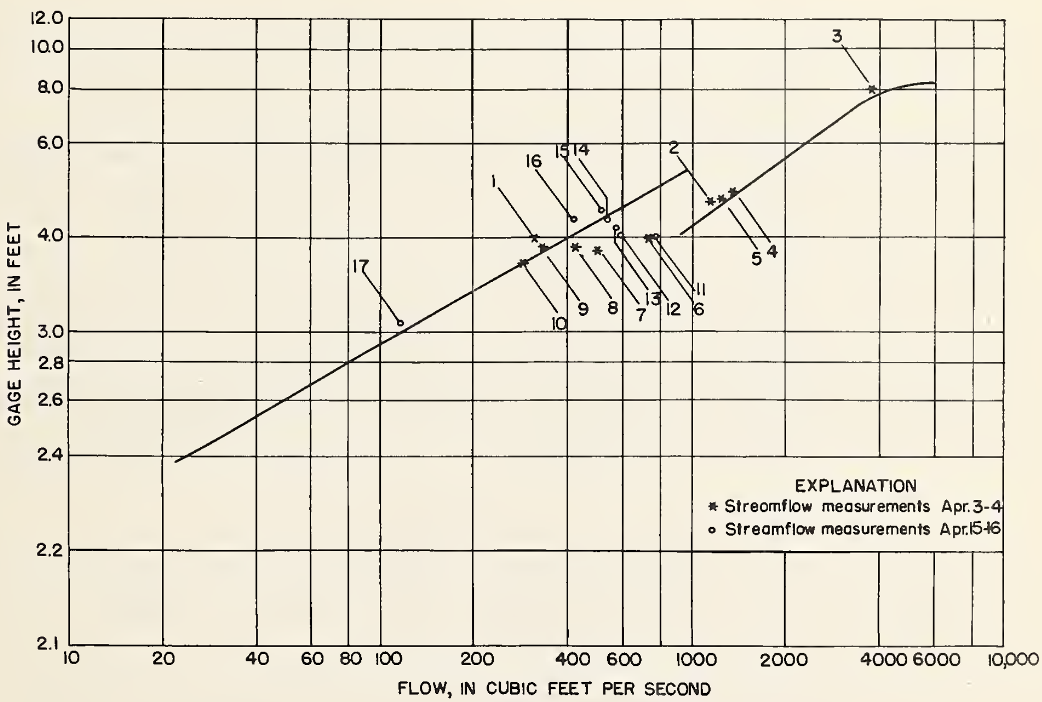


Figure 5.--Stage-discharge relationship for station 34 on Pigeon Roost Creek, Miss.

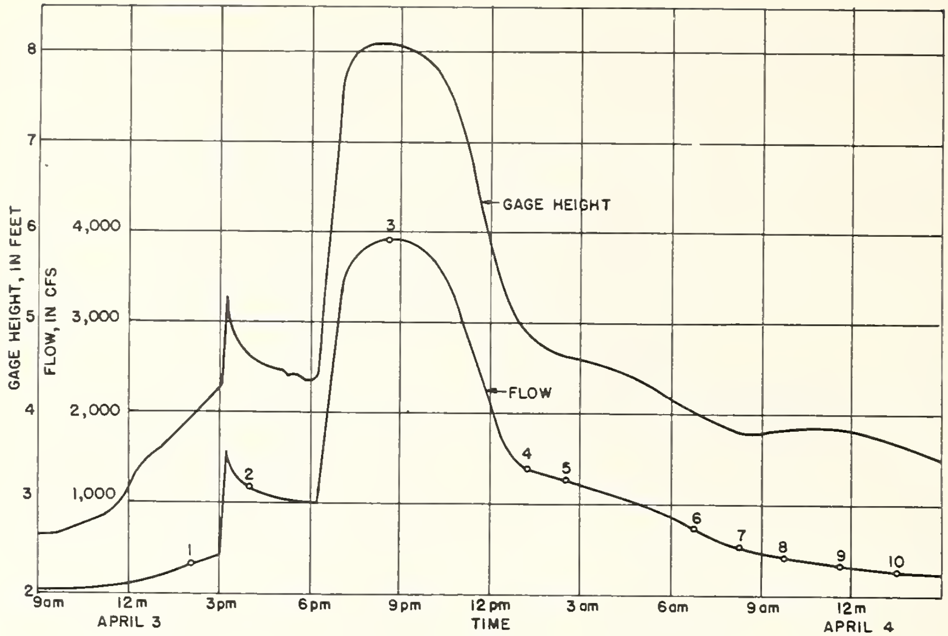


Figure 6.--Hydrographs of flow and gage height for the rise of April 3-4, 1958, station 34, Pigeon Roost Creek, Miss.

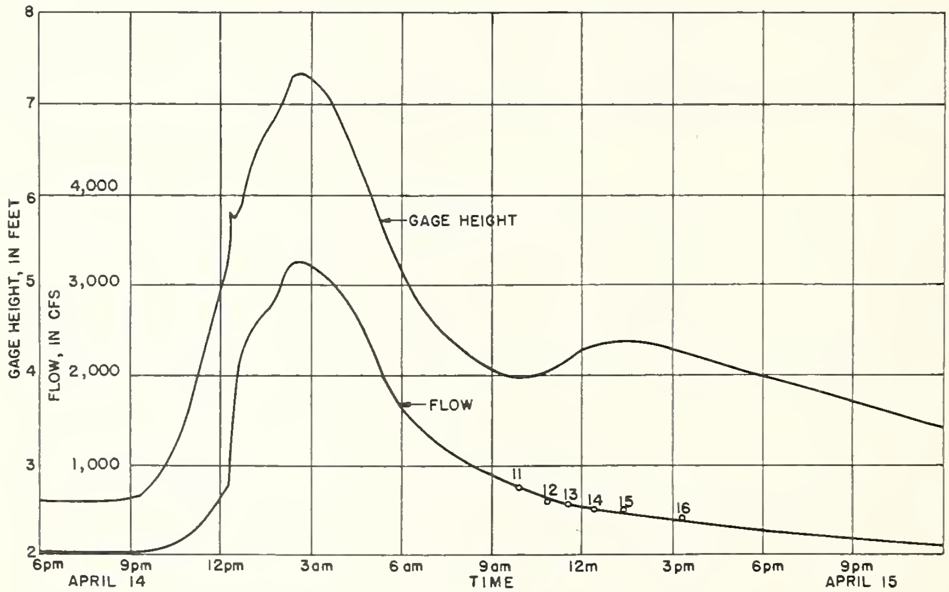


Figure 7.--Hydrographs of flow and gage height for the rise of April 14-15, 1958, station 34, Pigeon Roost Creek, Miss.

Streamflow measurements that definitely fall between the curves of figures 4 and 5 were all made when the flow was changing appreciably. A few hundred measurements being available, the stage-discharge relationship for steady flows at station 34 during the period covered by the records probably never was intermediate between the two curves.

The transition from one curve to the other on a rising discharge at station 34 can seldom be defined by the usual streamflow measurements, because the rise takes place rapidly. On April 3, visual observation of the velocities showed the change from the low-flow curve to the high-flow curve to have occurred within a few minutes. (This transition may sometimes, however, occur much more slowly, especially at some of the other gaging stations.) Soon after the velocity increased, large standing waves formed. A simple statement of the complex relationship is that the stage rises rapidly when the high velocities behind the transition cause the water to catch up with the slower moving water in the channel ahead of the transition. This is consistent with the observation that the abrupt rise may begin at any gage height that does not yet represent flow on the high-velocity part of the stage-discharge relationship. The abrupt rise is caused by conditions upstream, which may not be associated with any observations of flow at station 34 prior to the rise. Such a rise should indicate to some hydrographers that the transition occurred far upstream from station 34 and moved down with the flow.

The hydrographs of gage height and rate of flow during the rise of April 3-4 (fig. 6) and of April 14-15 (fig. 7) indicate reasonably normal recession curves of rate of flow, but, especially on April 15, the gage-height graph has a peculiar hump that began at a gage height of about 4.0 feet. Secondary humps like this occur when the velocity decreases rapidly. The 790 cubic feet per second measured between 9:33 a.m. and 10:10 a.m. on April 15 flowed at an average depth of 1.8 feet, whereas the lesser flow of 403 cubic feet per second that was measured between 3:05 p.m. and 3:30 p.m. on April 15 flowed at an average depth of 2.1 feet.

Although the recession in rate of flow was reasonably normal, two factors are likely to affect its shape to some extent:

First, a gage-height hump on the recession indicates that instead of draining normally the storage within a short reach of channel increases for a time. Hence, on April 15 when the stage was rising to the gage-height hump, channel storage was reducing the flow as it passed through the reach rather than increasing it. This departure from a steady rate of channel draining will cause at least minor irregularities in the recession of flow.

Second, the lag time between the generation of direct runoff and its discharge at the gaging station will be much different for flow at high velocity than for flow at low velocity. To some degree, therefore, two different runoff hydrographs might be thought to govern the flow from one storm. Perhaps one smooth hydrograph would be defined if all the flow could be discharged at velocities that are consistent with the high-velocity curve, and another smooth hydrograph with a lower peak discharge and longer base would be defined if all the flow could be discharged at velocities that are consistent with the low-velocity curve. When the lag time changes on the falling stage, the form of the recession curve of flow may not be smooth and normal.

On the recession side of a hydrograph, the gage height at which the transition begins has significance, because at this gage the hydraulic conditions must be the ones required to start the transition from high to low velocity. On the rising side of a hydrograph, the gage height at the beginning of the transition has significance only if the increase in discharge and stage has been gradual until conditions became established to cause the transition from low to high velocity. The gage height at which the transition is completed on the rising side of the hydrograph might also have significance if we could identify it from the gage-height record.

The time of the beginning of the shift from the high-velocity curve to the low-velocity curve cannot be determined exactly from the gage-height hydrograph. However, for 46 recession hydrographs during a period of 2 years, the shifts began at gage heights as low

as about 3.5 feet and as high as about 4.8 feet. At times the shifts following high flows appeared to begin at higher gage heights than those following lower flows. One of the reasons for differences in the gage heights of the shift from high velocity to low velocity was variation in the relationship between gage height and average depth of flow, or between gage height and hydraulic radius. Eleven times during the 2 years the low-velocity curve continued to apply when the peak gage height was more than 4.8 feet, which was the highest determined gage height for a shift from the high-velocity curve to the low-velocity curve. Once, the low-velocity curve applied at a peak gage height of 6.2 feet. Thus, within a wide range of gage heights the gage height alone does not determine which curve will apply.

The following illustrative example is given merely as an explanation for the range of stage over which either the low- or the high-velocity curve may be applicable. It does not mean that a particular discharge is a satisfactory guide as to which of the two curves is applicable. Suppose that a shift from the high-velocity curve to the low-velocity curve occurs at a gage height of 4.2 feet and a discharge of 1,000 cubic feet per second. Then, should a shift to the high-velocity curve from the low-velocity curve be expected at a gage height of 4.2 feet on a slowly rising stage? In other words, is it logical for the gage height to rise above 4.2 feet without a shift from the low-velocity curve to the high-velocity curve? If the transition did occur at 4.2 feet on a slowly increasing flow, it could not maintain itself because the rate of discharge would be only about 470 cubic feet per second (fig. 4), about half that at which the shift back to the low-flow curve should occur. If 1,000 cubic feet per second discharge is required for the high-velocity curve to apply on a gradually increasing flow, then a gage height of nearly 5.4 feet would be required for a transition. A flow of 960 cubic feet per second at a gage height of 5.3 feet would cause no shift from the low-velocity curve.

Station 17

Two discontinuous stage-discharge relationships similar to that for station 34 have been defined by streamflow measurements at station 17. The first one applied until about January 31, 1957, when the channel at station 17 aggraded about 0.9 foot. The second (fig. 8) has been applicable with small shifts from February 1, 1957, to at least December 31, 1958. When the first curve was applicable, the shift from the high-velocity curve to the low-velocity curve usually occurred at gage heights between 6.2 and 7.1 feet; when the second curve was applicable, the shift occurred between 7.2 and 8.0 feet. On March 26, 1959, a peak gage height of 9.36 feet was recorded without a shift from the low-velocity curve. All available information indicates that the low-velocity curves apply when dunes cover the bed and the high-velocity curves apply when the bed is plane or has antidunes.

In general, the abrupt rises, common at station 34 when the transition takes place from the low-velocity curve to the high-velocity curve, are less frequent at station 17. Often, the rising side of the gage-height hydrograph does not show that a shift has occurred. Also, the gage-height hump on the recession is less frequent at station 17 than at station 34 and is usually smaller and of shorter duration. Sometimes, the gage-height record gives little evidence of any kind that the stage-discharge relationship shifted during a rise even though streamflow measurements show that it did.

Station 12

The stage-discharge relationship for station 12 (fig. 8) is also discontinuous, at least for some rises. However, at this station, changes from one curve to the other are often indiscernible from the gage-height record alone. That is, the shift from one curve to the other seems to be gradual or even incomplete for some rises. When some wading measurements were made, part of the streambed was firm and comparatively smooth and part of the bed was covered with loose, irregular dunes. Velocities were high over the plane bed and comparatively low over the dune bed. (See fig. 9.) The bed configuration may change along the channel as well as laterally. Coexistence of two kinds of bed configuration

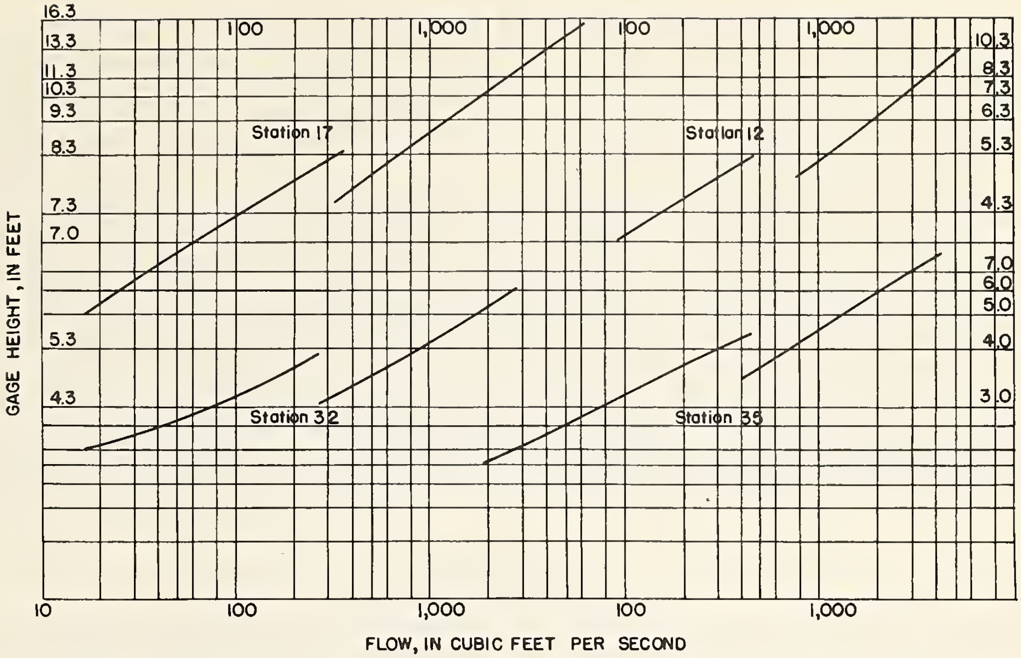


Figure 8.--Discontinuous rating curves for stations 17, 12, 32, and 35 on Pigeon Roost and Cuffawa Creeks, Miss.

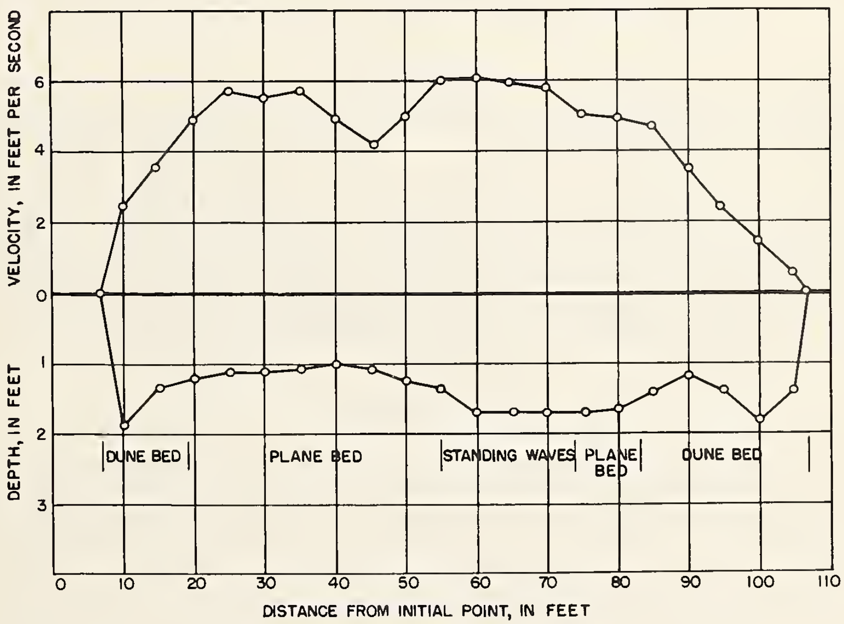


Figure 9.--Lateral distributions of velocity, depth, and approximate bed configurations downstream from station 12 on January 21, 1959.

is associated with nonuniform distribution of velocities and depths, and the velocities and depths at station 12 are less uniformly distributed than at stations 17, 32, 34, and 35. Perhaps at times the bed configuration may be intermediate between the dune and the plane bed, rather than a combination of the two configurations each distinctly developed over a part of the bed. Thus, the resistance to flow is likely to be variable and unpredictable for an appreciable range of flow.

Although the discontinuous stage-discharge relationships for stations 12 and 34 are comparable for a plane bed and a dune bed, the transitions between the two curves show important differences. Station 34 has relatively clear-cut transitions that probably could not be duplicated at steady flow. That is, streamflow measurements at steady flows may all plot close to one or the other of the two curves. At station 12, steady flows probably can occur when the streambed is neither wholly a plane bed nor a dune bed. Also, the transitions between flows over the two types of bed may require several hours to take place over the entire bed. Unfortunately, the behavior of flows at station 12 is probably much more representative of natural streams than is the behavior of the flows at station 34. The slowness and incompleteness of some transitions would account for the difficulty of defining a discontinuous stage-discharge relationship for many natural streams where such a relationship might be expected.

Station 32

Streamflow measurements define a discontinuous stage-discharge relationship (fig. 8) for station 32. Some rises have the abrupt increases in gage height on the rising stage and the pronounced gage-height humps that are typical of gage-height recession graphs at station 34. However, other rises show little evidence on the gage-height record of the shift from one curve to the other. As at station 12, part of the flow has sometimes been observed to be over loose sand dunes while part is over a firm and smooth bed.

Station 35

A discontinuous stage-discharge relationship was clearly indicated by the first few dozen streamflow measurements that were made at station 35. The relationship (fig. 8) was used during 1957 and 1958 with little change except temporary shifts. Sometimes the gage-height hump signals a shift away from the high-velocity curve and sometimes possible shifts from one curve to the other are indeterminate from the gage-height record alone. In common with the preceding four gaging stations, a shift at this station from the low-velocity curve to the high-velocity curve may not occur on a rise that produces a peak gage height appreciably higher than the gage heights at which the flow would shift back from the high-velocity curve to the low-velocity curve.

Other Stations

At seven other gaging stations on tributaries of Pigeon Roost Creek, the streamflow measurements do not define discontinuous stage-discharge relationships. Six of the stations have sand beds and one does not. The slope of the streambed is steeper at each of these stations than at any of the five stations for which the discontinuous relationships have been defined. If discontinuities occur at these seven stations, they are at shallow flows at which small and local shifts of the streambed can obscure even the large changes in discharge that accompany discontinuity in stage-discharge relationships. Moreover, at very low flows, routine streamflow measurements, if they are made at all, are frequently very inaccurate. The depth at shallow flows is likely to differ widely percentagewise across the stream, and two or three kinds of bed configuration may be found even in a narrow section. Thus, at a gaging station on Dry Fork Creek, which has a drainage area of 8.64 square miles and a bed slope of perhaps 0.004, three types of bed configuration have been observed within a width of flow of about 10 feet when the flow had a maximum depth of less than 0.2 foot. A narrow band of antidunes extending along the center of the channel was bordered by strips of plane bed. Irregular dunes were along each side of the channel.

APPLICATIONS TO THE MECHANICS OF SAND-BED STREAMS

Although streamflow measurements on Pigeon Roost and Cuffawa Creeks were made principally as a basis for computing yields of water and sediment, they also furnish useful information on the general behavior of sand-bed streams particularly with respect to resistance to flow. Several facts about this information should be kept in mind. First, field measurements are usually less precise than flume measurements. Second, flow and sediment loads are rarely constant over considerable periods of time, except at low flow. Hence, equilibrium may not be reached in the sense that it is reached in a laboratory flume after hours of operation for the purpose of obtaining a steady flow. In addition, measurements and observations cannot usually be repeated as a check or to supply omitted information. Third, the effect of individual factors cannot generally be studied by keeping other variables constant. However, in the present study some variables can be shown to be relatively constant. Fourth, the field determinations have the advantage of being to full scale and do not require results of water flow and sediment discharge in a very small channel to be questionably applied to larger channels. Fifth, the channels have many characteristics of a flume channel: They are generally straight; with some exceptions are relatively uniform in cross section; have stable (but not relatively frictionless) banks; and have beds of fairly uniform sand.

In general, a discontinuity in a stage-discharge relationship might be ascribed either to incorrect gage heights or to large and abrupt changes in (a) cross section with time and stage, (b) energy gradient, or (c) resistance to flow. The recorded gage heights have already been stated to be about representative of gage heights near the bank where the velocity is low. The probability of large and abrupt changes in the other three factors is further examined in the following three sections.

Constancy of Cross Section With Time and Stage

The banks of Pigeon Roost and Cuffawa Creeks are fairly stable and certainly do not shift abruptly. Discontinuities occur when the flow is within the banks of man-made channels. Any abrupt and large changes in cross section with time or with stage must be due to shifting of the streambed.

Both experimental information and simple reasoning indicate that on the average the bed of Pigeon Roost Creek at station 34, for example, does not scour deeply on a rise and then fill about an equivalent amount on the recession from the rise. Because the low-flow measurements at the station repeatedly plot within 0.2 or 0.3 foot of the same curve (fig. 4), the controlling section for the gaging station can reasonably be assumed to scour and fill relatively little during most high flows. Had the scour and fill been of great extent, the channel bed at the controlling section would not have returned to about the same position after each rise. Also, for the rise of April 14-16, 1958, the wading measurements, all made at the same cross section, showed little change in average elevation of the streambed on the recession of flow, although the mean velocity changed rapidly. (See table 2.) Average elevations of the bed at the measuring section were computed by dividing each cross-sectional area by the reported width, which was always about 74 feet, then subtracting each average depth so computed from the corresponding gage height. No adjustment was applied for the small amount of water-surface slope for the distance of less than 100 feet from the measuring section to the gage. The computed average elevations of the bed are surprisingly consistent, probably more so than would normally be expected, but even much larger changes in elevation of the bed would be entirely inadequate to account for the change in flow.

Along any appreciable length of uniform channel, large amounts of scour on a rising stage and subsequent fill to the original elevation on the falling stage are improbable, as can be shown by simple reasoning based on continuity. For example, consider a reach of channel that has stable banks, a bed of sand, and neither diversions nor tributary inflow; that is, a channel like that of Pigeon Roost Creek upstream and downstream from the bridge at station 34. (However, reasoning based on the principles of continuity is not

TABLE 2.--Streamflow measurements by wading at station 34 on April 15 and 16, 1958

Date	Midtime of measurement	Mean gage height	Mean velocity	Cross-sectional area	Flow	Average elevation of the bed (gage height)
		Feet	*Ft./sec.*	*Sq. feet*	*Cfs*	*Feet*
April 15.........	10:55 a.m.	4.04	4.18	141	590	2.14
April 15.........	11:35 a.m.	4.16	3.85	151	581	2.12
April 15.........	12:25 p.m.	4.32	3.35	158	530	2.18
April 15.........	1:25 p.m.	4.41	3.07	168	516	2.14
April 15.........	3:15 p.m.	4.32	2.57	157	403	2.20
April 16.........	9:50 a.m.	3.07	1.70	68.9	117	2.17

limited to such channels.) The first step in applying these principles is to show that changes in the amount of bed material in transport can explain only small amounts of scour or fill.

The weight of bed material being transported above the streambed at any particular instant is small even during high flows. In Pigeon Roost Creek or Cuffawa Creek measured concentrations of sediment of sizes found in the streambed (nearly all the bed material is coarser than 0.125 mm) are generally, even at high flows, only 0.2 or 0.3 percent of the water and sediment mixture by weight. Rarely do measured concentrations of bed material exceed 0.4 or 0.5 percent, and these highest measured concentrations of bed material may be incorrect because the sediment sampler can easily pick up excessive sand from the streambed or from the zone of very high concentration near the bed. At high flows the computed unmeasured sediment discharge, mostly bed-material sizes, is usually considerably less than the measured bed material. Therefore, total concentration of sediment of bed-material sizes may be around 0.5 to 0.8 percent of the weight of the water-sediment mixture at the peak of observed flows.

The depth of flow at the peak of the rise is usually 10 feet or less. For rough estimating, the depth of sand that would deposit on the streambed if it could all be deposited instantaneously may be assumed to have the same ratio to depth of flow as is given by the concentration of bed material. Hence, the amount of bed material in transport at any time at station 34 can safely be assumed to equal less than 0.1 foot of average depth of deposit on the bed of the channel if it could all be dropped instantly. Therefore, changes from time to time in the amount of bed material in transport within a channel reach can account for only small amounts of average scour and fill.

Two additional factors should, of course, be considered for more precise computations of depth of deposit that might result from instantaneous deposition of all the bed material in transport at a given instant. The first is that the dry weight of a cubic foot of sand (the bed material) is about 85 pounds at station 34 as compared to a weight of 62.4 pounds for water. Thus, the ratio of possible depth of deposit of bed material to depth of flow would be only about 75 percent of the ratio of dry weight of sands to total weight of water-sediment mixture. The second is that the measured concentrations of depth-integrated sediment samples are weighted with velocity, as are also the computed concentrations of unmeasured sediment discharge. The concentrations are based on more water-sediment mixture per unit of depth near the surface where the concentration of sand is lower than near the bed where the concentration of sand is higher. The percentage effect is probably small but not negligible in precise computations. It is probably considerably smaller than the adjustment for the difference in specific weight of the sands in place and the weight of a cubic foot of water.

If changes in the quantity of sediment in transport are small, large amounts of average scour or fill along a reach of uniform channel like that near station 34 must be due to the difference between inflow of bed material to the reach and outflow of bed material from it. A large amount of scour along a reach of uniform channel on a rise and equivalent fill on the following recession require two contradictory relationships. These are (a) during rising stages, generally much greater rates of bed material outflow from the reach than inflow to it and (b) during falling stages, generally much greater rates of bed material inflow to the reach than outflow from it. Such major reversals of relationship are highly unlikely and usually impossible in a uniform channel. However, large amounts of scour on a rising stage and fill on a falling stage frequently do occur at channel constrictions such as those at many bridges from which streamflow measurements are made. Large amounts of local scour and fill at pools and riffles are also common.

On the basis of the preceding information and discussion, the average elevation of the streambed away from the bridges on Pigeon Roost and Cuffawa Creeks is assumed to be relatively constant during most flood rises, although changes may occur at times. The channel at station 17 aggraded nearly a foot during a prolonged period of runoff at the end of January 1957, but this change was very unusual and may have been caused by backwater from a tributary. Presumably, the channel aggraded on both rising and falling stages. Certainly no consistent and appreciable amounts of scour on a rising stage and equivalent fill on a falling stage are usual in the channels away from the bridges.

Constancy of Energy Gradient

If the flow is constant along a uniform channel, the surface slope, the bed slope, and the energy gradient are all parallel. During periods of changing flow, the surface slope and the energy gradient differ somewhat from the bed slope; the amounts of the difference are limited by several factors. The most obvious limitation is that the surface slope can neither intersect the bed, if there is any flow at all, nor rise much above the banks of the stream and the level of the surrounding valley. Hence, large differences between surface slope and bed slope must extend only short distances along the channel and cannot last long in any given reach of channel.

The following crude computations give an idea of probable differences at station 34 between the average water-surface slope of 0.0011 for steady flow and the energy gradient during rapid changes of stage. The average water-surface slope is based on three determinations of 0.0010, 0.0012, and 0.0012. The first and last determinations were for flows on the high-velocity curve; the second was for a flow on the low-velocity curve. Assume that a rapid rise approaches the station. The gage height increases 1.0 foot in 10 minutes at the gage. At the beginning of the 10-minute period, the mean velocity at the gage is 2.5 feet per second. Upstream 1,000 feet from the gage, the mean velocity is 5.0 feet per second at the same time. If coefficients for velocity distribution in the cross sections are disregarded, the approximate difference in velocity head is 0.3 foot. The rate of movement of the flow might be about 6 feet per second, which means that about 3 minutes are required for the flood wave to travel 1,000 feet. Hence, 3/10 of the 1.0-foot rise in 10 minutes, or 0.3 foot, is about the amount by which the water-surface slope exceeds that for a steady state. The energy gradient is then 1.1 + 0.3 + 0.3 feet per 1,000 feet, or 0.0017. The difference between the water-surface slope of 0.0011 and the energy gradient is large for the brief time during which the gage height is very rapidly rising and the velocity is fast increasing, but the difference between a mean velocity computed from the average water-surface slope and that computed from the energy gradient would be about 25 percent. This difference would be much less if no transition occurred, that is if there were no rapid increase in velocity. Although the difference in energy gradient for steady flow and for the assumed rapid rise accounts for little of the observed large increase in mean velocity, the difference may be important in starting the transition to the high-velocity curve of the stage-discharge relationship.

A comparable rough computation for a rapid gage-height recession of 1.0 foot in an hour (compare with figs. 6 and 7) and a decrease in mean velocity from 5.5 to 5.4 feet per

second gives an energy gradient of about 0.00103 as compared to an average water-surface slope of 0.0011 for steady flow. According to this computation, the error in computing mean velocity from the average water-surface slope for steady flow is about 4 percent. The error is far less than 4 percent during most of the recession. Therefore, on a recession, the differences between bed slope, surface slope, and energy gradient may be safely neglected in a preliminary study of the discontinuity in the stage-discharge relationship. Furthermore, in a uniform channel, the bed slope remains relatively constant over long periods of time. Hence, the assumption can be made that the energy gradient is essentially constant during the transitions from the high-flow curve to the low-flow curve. The energy gradient will be somewhat higher, but perhaps not excessively higher, on rapidly rising stages.

Variability of Resistance to Flow

Large and abrupt changes in resistance to flow in Pigeon Roost and Cuffawa Creeks cannot be due to changes in bed material because the bed material is all relatively uniform. A little washing out of the fine sand may occur, but the resulting change in resistance to flow would be small and gradual. Streamflow measurements made on April 15 and 16, 1958, at station 34 during a recession in flow showed that the average bed elevation was constant (table 2), within the limits of accuracy of the data. If the energy gradient is assumed to have also been constant, the decrease in mean velocity and the decrease in flow were then necessarily due to a large and progressive increase in resistance to flow. Similarly, if the bed elevations and energy gradients at each of the stations are assumed to be constant, the discontinuous stage-discharge relationships of figures 4 and 8 show wide differences in resistance to flow. Computations of Manning's n have been made to give a more nearly exact idea of the variability of the resistance to flow.

Available field information, although far from satisfactorily accurate and complete, was used to approximate Manning's n for several rates of flow. Unfortunately, the cross sections and mean velocities of the high-velocity flows were nearly all measured from bridges and therefore are unrepresentative of averages for the channel away from the bridges. Even the measured rates of flow at the bridge sections may be somewhat inaccurate. Hence, for high-velocity flows the following roundabout method was used to compute the roughness coefficient in the Manning velocity equation

$$V = \frac{1.49}{n} R^{2/3} S^{1/2},$$

where V = velocity, n = resistance coefficient, R = hydraulic radius, and S = slope.

For each of the five gaging stations five wading measurements were selected of the highest flows to which the low-velocity curves should apply (table 3). These measurements and the appropriate average water slope (table 1) were used to compare the approximate n's. The hydraulic radius for each measurement was computed by assuming that the wetted perimeter equalled the measured width plus the average depth of flow. This is a convenient and satisfactory compromise (checked for some of the Pigeon Roost Creek gaging stations) between approximation of the wetted perimeter as equalling the width (for sections that have large width-depth ratios) and computation of the wetted perimeter as the sum of the width and twice the depth (for rectangular cross sections).

The 25 computed Manning's n's varied from 0.025 to 0.042 (table 3) and averaged 0.0325 for these low-velocity measurements. The average for a gaging station varied from 0.031 for station 32 to 0.034 for station 12. The five n's were most consistent for station 34 where the depths of flow were greater than at any other station and were least consistent at station 12 where the flow was shallower and the lateral distribution of flow was poorer than at the other stations.

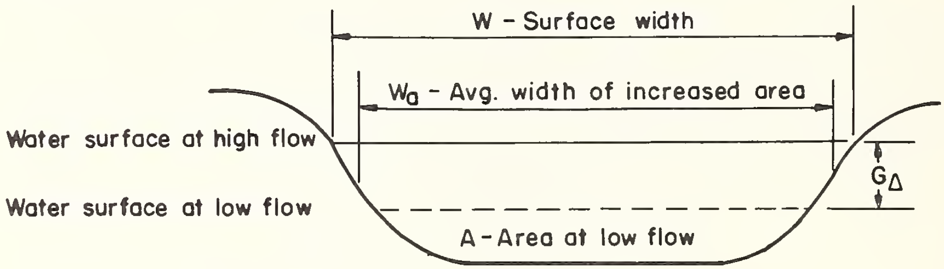
Because few wading measurements have been made when the high-velocity curve of the stage-discharge relationship applies, Manning's n for flow near the lower end of the

TABLE 3.--Approximate Manning's n's computed for 5 gaging stations, according to mean velocity and discharge, presenting the highest 5 low-velocity figures and their averages, the determination of the corresponding average figures as representative of the lower end of the high-velocity curve, and the determination of figures for high flow

Station 12			Station 17			Station 32			Station 34			Station 35		
Mean velocity	Discharge	Manning's n	Mean velocity	Discharge	Manning's n	Mean velocity	Discharge	Manning's n	Mean velocity	Discharge	Manning's n	Mean velocity	Discharge	Manning's n
HIGH ENDS OF LOW-VELOCITY CURVES														
Ft./sec.	*Cfs*		*Ft./sec.*	*Cfs*		*Ft./sec.*	*Cfs*		*Ft./sec.*	*Cfs*		*Ft./sec.*	*Cfs*	
2.81	216	0.027	2.55	177	0.025	2.63	263	0.030	2.71	623	0.034	2.34	182	0.033
1.64	121	.042	2.37	191	.031	2.88	284	.028	2.91	660	.030	2.76	326	.035
2.62	356	.035	2.01	178	.038	3.09	318	.026	2.71	545	.032	2.82	208	.027
2.46	204	.035	2.38	177	.032	2.55	280	.034	2.69	619	.033	2.20	188	.038
1.76	101	.033	2.71	282	.035	2.52	322	.037	2.58	437	.032	2.58	219	.031
2.34	200	0.034	2.40	201	0.032	2.73	293	0.031	2.71	577	0.032	2.54	225	0.033
LOW ENDS OF HIGH-VELOCITY CURVES														
5.98	510	0.013	5.50	460	0.014	7.60	820	0.011	5.56	1,180	0.016	6.15	540	0.014
HIGH FLOWS														
10.4	5,000	0.018	9.00	5,600	0.023	10.3	2,800	0.014	7.15	3,340	0.019	10.7	4,100	0.017

high-velocity curve was determined on the basis of two assumptions. The first is that the hydraulic radius at the average gage height of the five highest low-velocity measurements remained the same whether the low- or high-flow curve applied. This assumption follows directly from the constancy of the bed elevation. The second assumption is that the energy gradient is constant for steady or nearly steady flow. These assumptions mean that Manning's n is inversely proportional to the discharge. When the average discharge of the five low measurements, which were all made on recessions of flow, was computed for each gaging station, the discharge at the same gage height was taken from the high-velocity curve, which is applicable for steady flows. Then, the average n for the low measurements was multiplied by the ratio of the average discharge of the low-velocity measurements to the discharge as determined from the high-velocity curve. The resultant n was considered to be an average for high-velocity flows at shallow depths.

As the depth of flow increases, the effect of bank friction increases. The bank effect plus a possible change in resistance owing to antidunes along the middle of the channel at higher flows may increase the resistance to flow for the whole cross section. Hence, a high rate of steady flow was selected for each station at a stage for which the channel does not overflow and at which the stage-discharge relationship is reasonably well defined. The difference in gage height between this high flow and the previously used flow of the lower end of the high-velocity curve was determined from the high-velocity curve. The cross-sectional area for the high flow was obtained by adding the area for the lower flow to the increase in area that corresponded to the difference in gage height. (See fig. 10.) Then the hydraulic radius was computed for the total area. Manning's n was calculated on the assumption that the average water-surface slope was applicable for the high flow also. The Manning's n's (table 3) were consistently higher for the high flows than for the high-velocity flows at shallow depths at the same station. They were much lower than for the low-velocity flows.



Area at high flow equals $A+G_\Delta W_a$,

Depth at high flow equals $\dfrac{A+G_\Delta W_a}{W}$,

Wetted perimeter equals $W+\dfrac{A+G_\Delta W_a}{W}$ (approximately),

Mean velocity equals total flow divided by $(A+G_\Delta W_a)$ —

Where

A = Area at low flow;

G_Δ = Difference in gage height;

W_a = Average width of increased area;

W = Surface width.

Figure 10.--Sketch, not to scale, illustrating the computation of area and wetted perimeter for flows at different gage heights.

In spite of the uncertainties in the computations, some helpful information is given by the n's in table 3. First, the Manning's n's for the low-velocity flows are equivalent to a dimensionless Chezy coefficient ($C/\sqrt{g}$) of about 9, and second, the n's for the flows at comparable depths but high velocities are equivalent to a dimensionless Chezy coefficient

of about 20. These results of 9 and 20 are reasonably consistent with dimensionless Chezy coefficients that have been reported by Barton and Lin (2) for flow in flumes over dunes and plane beds, respectively.

Vanoni and Brooks (6) have shown that the large differences in resistance to flow over dune beds and over plane beds are due mostly to the bed configurations rather than to the sediment that is being transported. Combined laboratory and field information indicates that the low-velocity curve of a discontinuous rating curve like that of figure 4 is a rating curve for the typically high resistance of a dune bed. Similarly, the high-velocity curve is a rating curve for the typically low resistance of a plane bed.

The low Manning's n's, on the order of 0.014, for flows at the low ends of the high-velocity curves show the low resistance to flow over plane beds (table 3). Even the high flows, which are affected by bank resistance, have Manning's n's on the order of 0.018 (table 3). As these high flows usually are characterized by standing waves over antidunes along the middle of the channel, flow over antidunes must have low Manning's n's. Two determinations at relatively low flows and shallow depths when antidunes were on the bed and bank friction was negligible gave n's of 0.013; one determination, which had an abnormally high (probably unrepresentative) reported water-surface slope, gave 0.018. Thus, low resistance to flow can be expected for antidune beds as well as for plane beds.

An average depth of about 8.5 feet at station 17 gave an n of 0.023 for the flow of 5,600 cubic feet per second. This n probably includes more effect of bank friction than any of the n's for high flow at other stations. The average depth of flow at the other stations was only 3 to 6 feet for the highest discharges shown in table 3. The n (0.011) for the flow of 820 cubic feet per second at station 32 appears to be too low as compared to the other n's, and the mean velocity seems to be too high for the lower end of the high-velocity curve. Probably, an n of about 0.014 would be more nearly correct. Five wading measurements at station 32 that seemed to have been made during transitions between the two curves of the stage-discharge relationship had computed Manning's n's ranging from 0.017 to 0.019, averaging 0.018. Therefore, the average n for the high-velocity flows at shallow depths should be appreciably less than 0.018.

The mean velocities of nine wading measurements at station 12 indicated that flow was in some transitional or intermediate phase between low-velocity flow over dunes and high-velocity flow over a plane bed or antidunes. Manning's n for these nine wading measurements ranged from 0.017 to 0.026. The gage heights and discharges of these measurements ranged from 3.82 to 5.51 feet and 130 to 829 cubic feet per second, respectively, with no apparent correlation between n and either gage height or discharge. This somewhat random variation of resistance to flow is probably much more usual in natural streams than is the relatively clear-cut transition between the two curves of the discontinuous stage-discharge relationship at station 34.

The changes in resistance to flow that are discussed here are due mostly to changes in bed configuration and are those that can occur relatively rapidly. Of course, minor changes in resistance can result from changes in the form of the cross section (the hydraulic radius is a satisfactory parameter only for certain shapes of cross section), from changes in bank resistance, from changes in particle size or shape of the bed material, and from the kind and quantity of sediment in transport. These minor effects on flow may cause some complications but are thought to be insignificant as compared to the large and rapid changes that result from changes in bed configuration.

Streams That May Have Discontinuities

On the basis of the preceding information and discussions, a stage-discharge relationship may be expected to have a discontinuity definable by streamflow measurements, providing that the reach has all the following characteristics:

1. A bed of uniform and readily shifting sediment, which does not form distinct pools and riffles.

2. At some flows most or all the streambed is covered with loose sand dunes.

3. At some higher flows the bed of the stream is mostly plane or has antidunes. If the bed configuration cannot be directly observed, high mean velocities or standing waves are indications that dunes no longer cover the bed.

4. The depth of flow, at the time, must be great enough that the change in rate of discharge as a result of the change in resistance to flow can be distinguished from changes in discharge that are caused by small, local shifts of the channel bottom.

5. Velocities and depths must be distributed uniformly enough laterally for the bed configuration to change across most of the streambed within a relatively short time.

These conditions are very restrictive. Only certain reaches of a relatively few streams in the United States can be expected to show a marked discontinuity in the stage-discharge relationship, although many streams that have sandy beds can be expected to have variable resistance to flow. All streams with well-developed pools and riffles at the stage where the transition might otherwise occur probably are eliminated because the stage-discharge relationship in this case is determined primarily by the riffles and not by the bed friction within the pools. A few streams having suitable bed materials may never show the discontinuity because dunes exist even at the highest mean velocities. Others may have such high slopes that the low-velocity part of the relationship cannot be defined by current-meter measurements because the discontinuity is at too shallow depths. (If shear velocity is considered to be a rough measure of the depth at which a discontinuity will occur, a steep slope would indicate a shallow depth for the discontinuity.) Winding streams seldom have uniform lateral distribution of depths and velocities. Some streams have such gradual or inconsistent transitions between dunes and a plane bed that the discontinuity may be difficult if not impossible to define.

Shear Velocities as a Guide to Discontinuities

Obviously, a mathematical statement of the conditions for a given type of bed configuration would be very helpful. One based essentially on shear velocity has been suggested for study by Albertson, Simons, and Richardson (1). They give an empirical relationship for flume experiments between the shear-velocity Reynolds number and the ratio of the shear velocity to the fall velocity. If a water temperature of 70° F. is assumed and the fall velocities are substituted in their relationship, the shear velocity for the transition from a dune bed to a plane bed or vice versa is about 0.18 foot per second and for a plane bed to an antidune bed or vice versa is about 0.26 foot per second. These shear velocities are about constant for particle sizes from 0.1 to 1.0 millimeter.

For the five gaging stations, shear velocities were computed for a few times at the beginning of a transition from the high-velocity curve to the low-velocity curve. No computation was made unless a wading measurement of flow was available at about the correct time and gage height. Thus, only a few determinations were made for some of the stations. Average slope of the water surface, based on one to three measured slopes, was used for each station.

Meaningful gage heights for the <u>beginning</u> of the transition on a rising stage from the low-velocity curve to the high-velocity curve have not been obtained and may not be obtainable at most stations, but the shear velocity for the beginning of this transition can be approximated. Suppose that the gage height, hydraulic radius, average water-surface slope, and discharge are all known at the beginning of the transition from the high-flow curve to the low-flow curve of a discontinuous stage-discharge relationship. The gage height at the beginning of the transition away from the low-flow curve must, when the stage is increasing slowly, exceed the gage height for the first transition by at least the difference in gage height between the two curves where they overlap. Otherwise, the flow would immediately start shifting back to the low-velocity curve. The difference in the two hydraulic radii for

the beginnings of the two transitions must closely equal the difference in gage heights. If the rise is abrupt, the slope will be steeper than for steady flow but the gage height at which the minimum necessary discharge occurs will be reduced. Hence, the shear velocity for a given discharge should be roughly the same whether the rise is slow or abrupt. Therefore, in these determinations, the difference in gage height between the curves where they overlap is added to the hydraulic radius at the beginning of the transition away from the high-flow curve to obtain the approximate hydraulic radius at the beginning of the transition away from the low-flow curve. The resulting hydraulic radius and the water-surface slope for steady flow accordingly were used to compute the shear velocity at the beginning of the transition from the low-velocity to the high-velocity curve. (No discussion of possible lag of resistance during rapid changes of flow is given here.)

The shear velocities computed for each transition are reasonably consistent from station to station (table 4). However, the shear velocity averaging 0.27 foot per second for the beginning of the transition from the high- to the low-velocity curve is 50 percent higher than the 0.18 foot per second that was computed from the relationship given by Albertson, Simons, and Richardson (1). The shear velocity averaging 0.35 foot per second for the transition from the low- to the high-velocity curve is nearly double the shear velocity of 0.18 foot per second. In fact, these shear velocities in the last column of table 4, although an upper limit for dune beds, are in the antidune range of the graph suggested by Albertson, Simons, and Richardson. Thus, the field data, admittedly not exact, indicate a disagreement with the suggested graph both in magnitude of the shear velocities and in showing a wide range of shear velocities for which either a low-velocity curve or a high-velocity curve may apply.

TABLE 4.--Shear velocities at the transitions between types of flow

Station No.	Approximate slope	Beginning of transition from plane bed to dune bed			Difference in gage height between curves	Shear velocities	
		Determinations	Range of hydraulic radius	Average hydraulic radius		Beginning of transition away from plane bed	Transition from dune bed to plane bed
		Number	*Feet*	*Feet*	*Feet*	*Ft./sec.*	*Ft./sec.*
12...........	0.002±	3	0.9-1.3	1.1	0.9	0.27	0.36
17...........	.0015	4	1.6-1.8	1.7	.9	.29	.35
32...........	.0020	11	.8-1.3	1.0	.8	.25	.34
34...........	.0011	12	1.6-2.2	1.9	1.1	.26	.33
35...........	.0018	3	1.2-1.6	1.4	.8	.28	.36

In addition, shear velocities for some of the highest peaks of runoff to which the low-velocity curve applied were computed for station 34. Seven determinations of hydraulic radius for these high peaks ranged from 2.8 to 3.7 feet and averaged 3.1 feet. For the water-surface slope of 0.0011, the indicated average shear velocity is 0.33 foot per second, which checks exactly, partly by coincidence, the 0.33 foot per second given in table 4 for station 34 and confirms the wide range of shear velocities for which either the low- or the high-velocity curve may apply.

As the shear velocities in table 4 are based on generally much deeper flows than are used in flume experiments, a few shear velocities were computed for shallow flows in natural streams. For flows at depths of 0.86, 0.46, and 0.31 foot over plane beds or antidune beds, the shear velocities were 0.26, 0.22, and 0.19 foot per second, respectively. They were based on measured cross sections, mean velocities, and water-surface slopes. Of course, they are higher by some unknown amounts than the shear velocities for the transition from a plane bed to a dune bed. They indicate, but do not prove, that the shear velocity of 0.18 foot per second from the graph suggested by Albertson, Simons, and

Richardson may apply more closely at shallow depths than at depths of 1 foot or more. In general, however, no satisfactory mathematical guide is yet available to predict from the hydraulic radius and energy gradient whether flow will be on the low-velocity curve, the high-velocity curve, or between them.

General Implications

Field data from Pigeon Roost Creek and Cuffawa Creek and the preceding discussions have some broad implications in studies of flow over sandy streambeds. Table 3 and the explanation of the stability of the sandy beds of uniform channels (p. 15) show that a change in resistance to flow may require a change in the elevation of the water surface. That is, appreciable changes in the elevation of the streambed result from differences between the inflow and outflow of bed material to and from a reach of channel. Therefore, if a change in resistance to flow requires an adjustment in the depth of flow, that adjustment causes a change in the elevation of the water surface, unless through an unlikely coincidence the channel bed scours or fills an exactly counterbalancing amount. Changes in depth of flow through a pool because the bed varies should not be confused with changes in depth of flow resulting from changes in resistance to flow.

The big difference in resistance to flow over dune beds and over plane beds is generally recognized, but the implications of this difference sometimes are not. Consider a wide, rectangular uniform channel that has a bed of uniform sand that will be in dunes at some depths of flow and in a plane bed at other depths of flow. Manning's n is 0.030 for the dune bed and 0.015 for the plane bed. (If depth and slope are constant, Manning's n is inversely proportional to the discharge.) Slope, composition of the bed, and water temperature are all considered to be constant. The maximum depth of flow over a dune bed is 2.0 feet for this channel. If the mean velocity is 3.0 feet per second over the dune bed at the depth of 2.0 feet (6.0 cfs per foot of width), it would be $\frac{0.030}{0.015} \times 3.0$, or 6.0 feet per second (12.0 cfs per foot of width) over a plane bed at the same depth. What will happen if a steady flow of 9.0 cubic feet per second per foot of width is introduced into the channel? Four possibilities suggest themselves:

1. The channel cannot carry 9.0 cubic feet per second per foot of width as a steady flow. This is an illogical consideration.

2. The flow will be at the depth that would give a discharge of 9.0 cubic feet per second per foot of width over a plane bed or 4.5 cubic feet per second per foot of width over a dune bed.

3. The Manning's n will be between that for a dune bed and that for a plane bed and the depth will be greater than 2.0 feet.

4. Manning's n will be between that for a dune bed and that for a plane bed, but the depth may be less than 2.0 feet. This is simply a combination of possibilities 2 and 3.

Possibility 1 follows directly from the assumption that one or the other of the two widely different Manning's n's applies and that the depth and slope uniquely determine the mean velocity. However, how can a channel be able to carry steady flows per foot of width of 0 to 6 cubic feet per second and 12 and more cubic feet per second but not intermediate flows such as 9 cubic feet per second?

Possibility 2 results from the idea that Manning's n may be either 0.030 or 0.015 for some ranges of depth and the shear velocity is thus not a unique measure of the mean velocity. The usual behavior of the streamflow at station 34 is generally consistent with this idea. The depth-velocity relationships during transitions at this station probably could not be duplicated at steady flow.

Possibility 3 implies that Manning's n may vary over a wide range even at steady flow; the shear velocity may still uniquely determine the mean velocity, but over a range of transition very small changes in depth will accompany large changes in mean velocity and in resistance to flow. Einstein and Chien (5) give a computed rating curve that illustrates this possibility. A reasonable assumption is that the shear velocity will be a poor and variable measure of mean velocity within the range between the maximum depth of flow over dunes and the minimum depth of flow over a plane bed. Possibility 3 may be inconsistent with the assumed channel although it may express the usual relationship for many natural streams that do not have rectangular cross sections.

Possibility 4 means that for a range of depths the shear velocity does not uniquely determine the mean velocity and also that the resistance to steady flow may be for flow over a dune bed, flow over a plane bed, or something in between. Within this range of depths, the flow may be indeterminate except as a very crude approximation. Possibility 4 probably represents the behavior of certain sand-bed streams better than any of the less complex possibilities.

COMPUTATION OF STREAMFLOW

A discontinuous stage-discharge relationship creates several problems in computing streamflow records. The primary problem is to recognize the existence of a discontinuity in the stage-discharge relationship at a gaging station so that plans can be made to define both curves without waste effort. In general, as has been shown, the discontinuity results from the difference between resistance to flow over sand dunes and that over a plane sand bed. Probably many streams have small differences in flow for a given hydraulic radius and energy gradient, because of differences in the resistance of the sand bed to flow. However, only discontinuities in the stage-discharge relationship large enough to be defined by usual streamflow measurements are considered in this discussion. The five conditions indicating the probable existence of a significant discontinuity have already been stated and should be kept in mind.

No discontinuities have been defined at stations on Pigeon Roost or Cuffawa Creek for the transitions, which do occur, from a plane bed to antidunes, or vice versa. The resistance to flow over antidunes may differ too little from that over a plane bed to cause a significant discontinuity. Also, the antidunes form initially and often are found later over a narrow band along the middle of the stream channel rather than across the entire width, and therefore their resistance affects only part of the flow.

Evidences of Discontinuities

Direct observation or measurement is the best indication of a stage-discharge discontinuity. Visual observation of velocities on a rising or falling stage should usually show a competent hydrographer whether or not such a discontinuity existed during that particular rise. A series of streamflow measurements made during a recession is the most certain way to define a discontinuity in the stage-discharge relationship. For maximum information on stream behavior, such a series of measurements should be made at a reasonably representative cross section of the channel, preferably at the controlling section for a gaging station. Bridge sections are seldom representative. If possible, all measurements in the series should be made at the same representative cross section.

In the absence of field observations, the appearance of the recorder chart is usually the best available guide as to whether the flow is on the high-velocity or the low-velocity curve or in transition between them. An abrupt and rapid rise to a gage height that is consistent with high-velocity flow may be part of a transition to the high-velocity curve. Violent surges on the recorder chart may show that standing waves existed, hence that the flow was at high velocity. At many stations the secondary hump on the recession of the gage-height graph is probably the best indication of a return to the low-velocity curve. Occasionally, on a particular stream the time of travel of peaks from one gaging station to another may help show weather the flow at the peak was at high or at low velocity.

Sometimes no recognizable evidences of a change in bed configuration or in resistance to flow will be available unless the bed configuration, the appearance of the water surface, or velocities have been observed in the field.

Defining the Discontinuous Stage-Discharge Relationship

After a discontinuity, such as that at station 34, has been found in the stage-discharge relationship, the hydrographer need obtain only enough measurements of flow to define both the low- and high-velocity curves and perhaps make an occasional series of measurements on the recession side of a hydrograph throughout the range of the discontinuity. Subsequent measurements are required only frequently enough to determine shifts from the defined curves. Any measurement made during the transition from one curve to the other does not apply directly in defining either curve and has comparatively little value except to determine the form of the recession of flow.

One major mistake to avoid is the use, as a basis for the upward extension of a high-velocity curve, of measurements made during a transition with the measurements made at the lower end of the high-velocity curve. This might have been done on figure 4 if no measurements had been made at gage heights above about 5.0 feet. Such a mistake might result in a stage-discharge relationship that would give far too large computed flows at gage heights above 6.0 feet. If the upward extension of the high-velocity curve is questionable, the flow through the controlling cross section of the channel should be computed for several gage heights for a constant or slowly changing value of Manning's n. A curve based on these computed flows should indicate the approximate trend of the upward extension of the high-velocity curve.

The two curves of the stage-discharge relationship are less easy to define at a station like station 12 because more of the streamflow measurements are made when neither curve applies. Thus, the sorting of the measurements into those applicable to each curve and those that represent transitional flows is more difficult. Of course, Manning's n's could be computed, and the measurements having Manning's n's about 0.03 or higher (table 3) could be used to define the low-velocity curve and those having n's lower than about 0.016 could be used to define the high-velocity curve. A simpler classification can be based on mean velocities. At station 12 measurements having mean velocities less than about 3 feet per second usually can be used to define the low-velocity curve; those having mean velocities greater than about 5 feet per second can be used to define the high-velocity curve. The actual mean velocities to use as guides will depend on depth of flow and probably some other factors.

At station 12 a continuous rating curve could be drawn through the lower part of the low-velocity curve, some transition measurements, and the middle and upper part of the high-velocity curve. However, some measurements at the upper end of the low-velocity curve and the lower end of the high-velocity curve would be far from the curve. Therefore, if these measurements and others in the transition zone were used as the basis for determining shifts at either high or low flows, the computed discharges might be far from correct. A discontinuous rating curve is preferable because it shows which measurements are in the transition zone and hence questionable as a basis for determining shifts at any time and gage height other than those occurring when each measurement was made.

Applying the Discontinuous Stage-Discharge Relationship

After being defined, the high- and low-velocity curves can readily be applied, with appropriate shifts, to compute rates and volumes of flow during those periods for which each applies. Within the periods of transition, the gage heights have no definite relationship to flow, so cannot be used directly for computing the flow within the transitions. On the rising side of the hydrograph, the transition may last so short a time at some gaging stations that the assumption of an instantaneous change from the low-velocity curve to

the high-velocity curve is usually satisfactory. If the rise is gradual, rates of flow may be based on an assumed hydrograph of flow during the time, usually short, when neither curve applies. On the falling stage, at some gaging stations, the flow may be computed from a curve based on rates of flow during the periods preceding and following the transition. That is, the high-velocity curve may be applied, with any indicated shifts, to some gage heights just before the transition starts, and the low-velocity curve can similarly be applied to some gage heights just after the transition has ended. A curve can then be drawn through the instantaneous rates of flow that have been thus determined. Then it is possible to take discharges during the transition directly from the curve. This curve may not have the usual form of a normal recession curve, because the secondary hump in the gage-height record indicates that there are abnormal changes in channel storage. The hydrograph may be abnormal also because the higher flows have a much shorter lag time than the lower flows. Of course, some decrease of lag time with increasing stage is relatively common, but the decreases are not so large as may result from the discontinuity in the stage-discharge relationship.

At station 12, and occasionally at stations 17 and 32, a graph of flow during transitions may be difficult to draw. The beginning and end of the transition may be indeterminate. For considerable periods of time, part of the flow may be over a plane bed and part of the flow may be over a dune bed at the same cross section. Perhaps this condition occurs only while the rate of flow is changing, but more probably it is rather usual even at steady flow in channels in which the flow and depth are unevenly distributed. This intermediate type of flow is sometimes difficult or even impossible to distinguish from typical high- or low-velocity flow by the gage-height record alone.

To make reasonably accurate computations of discharge within the range of gage height where the flows are usually relatively independent of the gage heights, it is at times necessary to take frequent streamflow measurements. Indeterminate or questionable transitions, such as frequently occur at station 12, are probably more usual in natural streams than are the comparatively clear-cut transitions that are characteristic at station 34.

COMPUTATION OF SEDIMENT DISCHARGE

Two general methods are frequently used to compute the sediment discharge of natural streams. In one method, sampled concentrations are the basis for drawing a continuous curve of measured sediment concentration. Concentrations from the curve are multiplied by rates of flow and an appropriate constant to obtain the discharges of the measured sediment. The other method is to prepare a curve of average relationship between either sediment discharge or concentration and rate of water discharge. The average curve may be based on measured sediment discharges or on computed sediment discharges. It may be shifted from time to time. If enough accurate sampled concentrations are available for the first method, the errors in computed sediment discharges are about proportional to the errors in the computations of streamflow. If an average relationship of sediment concentrations or discharges to rate of flow is used, the errors in streamflow records may be magnified two or three times in the sediment discharges computed at the incorrect rates of flow. This is because the sediment discharges may vary as the second or even a higher power of the discharge.

Large variations in resistance to flow may cause errors in computed sediment discharges in several ways. One way is through an incorrect assumption that a secondary gage-height hump like that on the recession curve of figure 7 represents increased flow from a second storm or delayed flow from storage or a tributary and hence a marked increase both of flow and of concentration of measured sediment. Conversely, a low-velocity curve might be used for a small peak for which a high-velocity curve should have been applied. Another large source of error might be in the computation of unmeasured sediment discharge, which varies roughly as the third power of the mean velocity if depth and measured concentration of bed material are constant. If the mean

velocity is greatly in error, as it can easily be for stations where the resistance to flow varies widely and rapidly, the computed unmeasured sediment discharges may be very inaccurate.

For the rise on April 3 and 4, 1958, at station 34, measured sediment concentrations, measured sediment coarser than 0.125 millimeter (loosely called sands), and unmeasured sediment discharge plus measured sands are plotted together with flow on figure 11. The concentrations of measured sediment plot reasonably close to the average curve, which is well defined throughout the rise. The concentration curve shows no close relationship to flow. This is entirely logical as most of the measured sediment is fine material, and the concentration of the fine material is related more nearly to the generation of runoff over the drainage area than to the rate of flow at the outlet of the basin.

Sampled concentrations of measured sands are highly variable. This variation is due partly to actual short-term fluctuations of the concentration of sands in the sampled zone and partly to the inaccuracy of sampling procedures. The average curve of concentration of measured sands is somewhat poorly defined (fig. 11) in spite of the frequent sampling. Also, the changes in this curve are not well understood. For one thing, the concentration of measured sands tends to follow the trend of the curve of measured sediment concentration of all particle sizes. In other words, the concentration of the fine sediment seems to have an effect on, or to correlate with, the concentration of measured sands, even when the velocity and depth of flow are changing little. If this is generally true, which it may not be, the significance of flume studies of sediment transport that involve no fine sediment might be questionable.

The apparent increase in average concentration of measured sands from 5 a.m. to 8 a.m. on April 4 was of particular interest. This sort of relationship has been observed on other recessions of flow, but it is not known whether the concentration of sands actually increased or whether the samples were somewhat misleading. Some difference in relative vertical distribution of the sands in the flow is likely when the bed configuration changes from a plane bed to a dune bed. The apparent increase in concentration started about the time the transition began from the plane bed to the dune bed, but the measured concentration of sands was again decreasing before the transition was complete. In general, the concentration of measured sands during the rise of April 3 and 4 at station 34 tended to be high at changes in flow or in bed configuration and then to decrease with time after a change. Thus, the measured concentrations of sands were comparatively high (a) at the time of the first abrupt increase in flow and the accompanying change in bed configuration, (b) at the second abrupt increase in flow, and (c) at the beginning of the change in bed configuration on the recession. A pertinent but unanswered question is whether the measured concentrations of sands are higher at and following each of these changes than they would have been for the same flows at a steady state.

Of course, the total concentration of sands is more significant than the measured concentration of sands. Hence, the equivalent concentration of unmeasured sediment discharge, which is mostly sands, was computed and added to the measured concentrations of sands to obtain the total concentration of sands. The estimates of unmeasured sediment discharges were based on mean velocities and on the concentrations of measured sands for given depths and velocities according to a method suggested by Colby (4). Concentration of measured sands has a variable relationship to the computed total concentration of sands; sometimes less than one-third of the total concentration of sands was measured. However, the curve of concentration of total sands shows the same general relationship, or lack of relationship, to streamflow as does the curve of concentration of measured sands.

Generally, the concentration of bed material in movement (or of sands, for a stream that has such a bed) has a rough relationship to mean velocity. Points on the average curve of concentration of measured sands plus unmeasured sediment discharge (fig. 11) are plotted against mean velocity on figure 12. For a given mean velocity, the concentration was usually higher than average immediately following an increase in velocity. It then

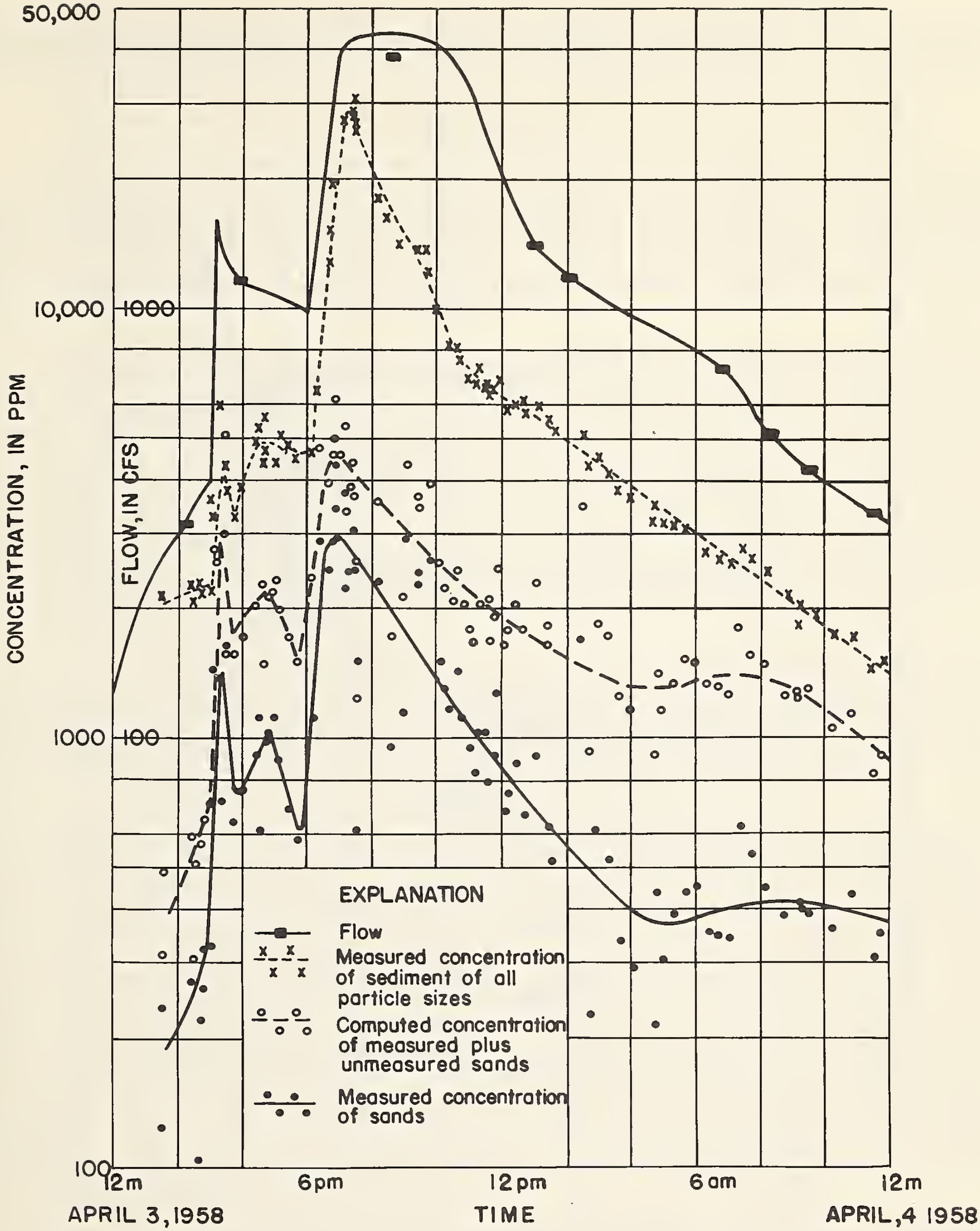


Figure 11.--Variations of flow and concentration during rise of April 3-4, 1958, at station 34 on Pigeon Roost Creek, Miss.

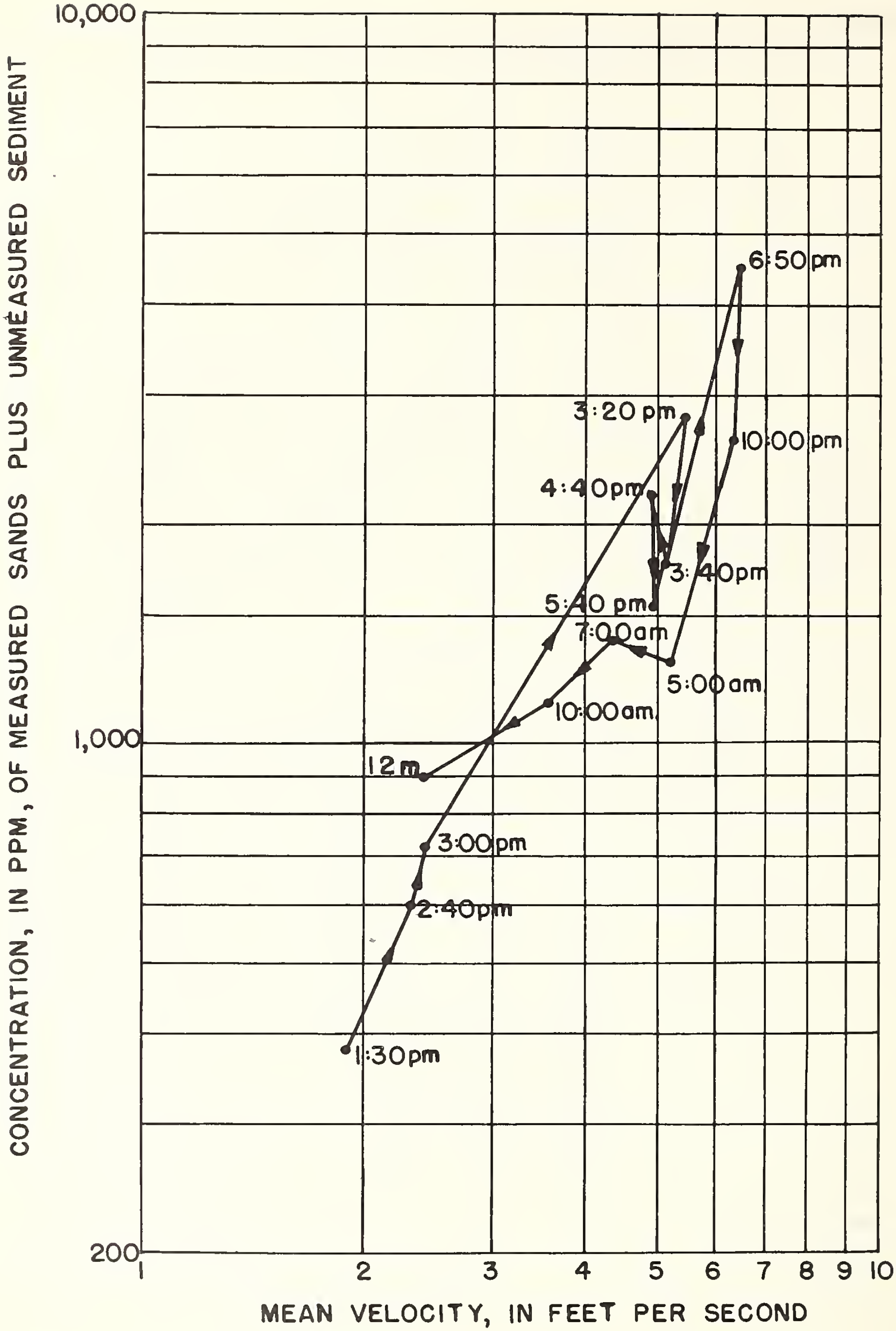


Figure 12.--Relationship of computed total concentration of sands to mean velocity.

decreased with time when the velocity was decreasing slowly. However, only inexact relationships have been defined for computing the discharge of sands from characteristics of the flow or geometry of the channel at stations on Pigeon Roost and Cuffawa Creeks.

SUMMARY

The channels of Pigeon Roost Creek and the lower part of its major tributary Cuffawa Creek are straight and have been excavated through flat bottom land. The stable, brushy banks scour very little. The streambeds are relatively level from bank to bank, consist of unusually uniform sand (median diameter 0.4 mm), and have slopes of about 1 or 2 feet per 1,000 feet. The slopes of tributary streams are usually much steeper but, except for the small streams, the beds are mostly sand.

Streamflow measurements for five gaging stations on Pigeon Roost and Cuffawa Creeks define discontinuous stage-discharge relationships. At some intermediate stages, the flow at times may be double that at other times for the same gage height. Above and below the rather narrow range of uncertain discharge, the measurements plot reasonably close to average curves. The low-velocity curve represents the stage-discharge relationship for flow over a bed of loose sand dunes, and the high-velocity curve represents the relationship for flow over a plane bed or combination of plane and antidune bed. At six other gaging stations, which have beds of sand but steeper slopes, the stage-discharge relationships show no apparent discontinuity. Probably any discontinuity is either indefinite because of poor lateral distribution of flow in the channel, or the discontinuity is at too shallow flows to be distinguishable by ordinary streamflow measurements from small, local shifts of the streambed.

The water-surface slopes and the average elevation of the sand bed are relatively constant at each station for which discontinuities in the stage-discharge relationship were defined. The discontinuities are due to much lower resistance to flow at some times than at others at the same gage height. When the velocities are high and resistance is low, the streambed may be relatively plane or have standing waves above antidunes along the middle of the channel. Intermediate bed configurations also may exist at times.

Manning's n is on the order of 0.030 for low-velocity flow in Pigeon Roost and Cuffawa Creeks and 0.015 for high-velocity flow at shallow depths. These resistances are reasonably consistent with those for some flume experiments with flow over sand dunes and over plane beds. Manning's n for high-velocity flows increases somewhat as the depth of flow increases and bank friction has more effect. At shallow depths, the resistance to flow at times may be anywhere in an approximate range from 0.015 to 0.030 for a transition from a plane bed to a dune bed or at some stations for a combination of dune bed and plane bed. At stations where the whole bed changes from dunes to a plane bed or vice versa at about the same time, a discontinuity in mean velocity at steady flow occurs. This does not mean a discontinuity in discharge per unit width of channel, because the depth of flow can adjust itself to the resistance and discharge. The adjustment ordinarily causes the water surface to rise or fall, while the elevation of the bed remains about constant. In order that all rates of discharge per foot of width may be possible at these stations, the depth of flow at low velocity must sometimes be considerably greater than the depth at other times when the velocity is high. Thus for a range of depth the shear velocity is an inadequate measure of mean velocity.

Discontinuities definable by streamflow measurements are to be expected in channels that have: (a) Beds of uniform sand, (b) a dune bed at some flows and a plane bed or a combination of plane and antidune bed at some higher flows, (c) uniform lateral and longitudinal distribution of flow, and (d) slopes low enough for the transition to occur at appreciable depths of flow. Few channels have all these characteristics. Uniform sand beds and uniform distribution of flow are rare outside of flumes. This is why discontinuous stage-discharge relationships in natural streams have seldom been defined. If the distribution of flow is not uniform, a continuous stage-discharge relationship may be defined

even though the other requirements for a discontinuity are present. However, the relationship is likely to be unstable in the range of stage for which the streambed is a combination of dune bed and plane or antidune bed or is an intermediate form between the two.

Satisfactory streamflow records can be computed from the two curves of a discontinuous stage-discharge relationship and from interpolated curves of instantaneous discharge during periods when neither the low- nor high-velocity curve applies, if the transitions are clear cut. That is, the streamflow records can be computed with generally sufficient accuracy if the entire bed of the channel has only one type of bed configuration at a time except for brief periods of transition. Frequent streamflow measurements may be required if different bed configurations exist within a short reach of channel for considerable periods of time.

Computation of the discharge of fine sediment is probably as accurate for stations that have large differences in bed resistance as at other stations if the streamflow can be computed accurately. Either kind of station requires periodic determination of the concentration of the fine sediment. For stations that have large differences in resistance, both sampling of the concentration of coarse sediment and computation of its discharge may be appreciably less accurate if the resistance and bed configuration vary. The decreased accuracy is likely even though the streamflow could be computed satisfactorily, something not always possible.

At stations where the streambed may have different configurations across a section or along a short reach of channel, the resistance to flow may be indeterminate for considerable periods of time. At such stations a definite discontinuity in the stage-discharge relationship may or may not exist.

Additional studies are badly needed of three problems that are discussed in this report. The first is the development of better guides to the actual time of occurrence of transitions from one part of a discontinuous stage-discharge relationship to another on both rising and falling stages. The second study needed is a broad investigation of methods for determining streamflow during times longer than a few hours when the entire streambed is neither a dune bed nor a plane bed; that is, when the transitions between the two curves of the discontinuous stage-discharge relationship are not clear cut. The third study needed is development of more satisfactory methods of computing bed-material discharges from the characteristics of the flow, channel, and sediment that is transported.

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